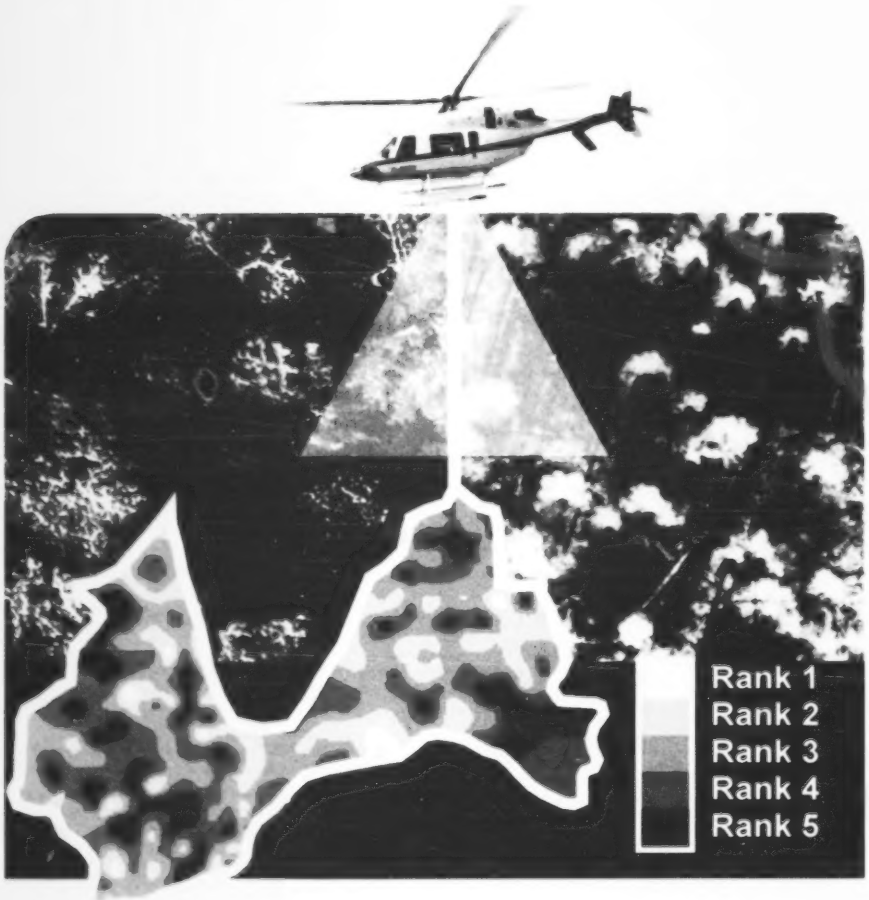
Forest Research Information Paper **170**

A proposed method to rank the intensity of boreal forest fires in Ontario using post-fire high-resolution aerial photographs



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A proposed method to rank the intensity of boreal forest fires in Ontario using post-fire high-resolution aerial photographs

T. Smith, B.D. Dalziel and R.G. Routledge

2008

Ontario Forest Research Institute
Ontario Ministry of Natural Resources
1235 Queen Street East
Sault Ste. Marie, Ontario
Canada P6A 2E5

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Abstract

Fire intensity is a crucial descriptor of fire behaviour that may also be an important determinant of many types of ecological dynamics. However, fire intensity has proven challenging to measure directly. Indirect estimates of fire intensity are often confounded with the ecological effects of the fire, precluding further study of the relationships between intensity and population or community dynamics. In this report, we describe a novel method for estimating the intensity of fires in the boreal forest of Ontario using high resolution imagery taken soon after fire. This method relies on an empirical relationship between the branch structure of fire-killed trees (crown fraction burned) and fire intensity rankings provided by the Canadian Forest Fire Behaviour Prediction System (FBP) and its field guide for fire managers. We describe the results of the application of this method to 660 high resolution aerial photography sample plots, each 25 m in diameter, dispersed among 11 fires that occurred in the boreal forest of Ontario in 2005. We were able to rank fire intensities into 5 groups, that are equivalent to <10, 10-500, 500-2000, 2000-4000, and >4000 Kw·m^2 in the FBP. The proposed method could be a useful proxy for the expensive instrumentation required for direct fire intensity measurements, and may represent a useful tool for forest and fire managers and research on fire-forest interaction at a variety of scales.

Resumé

L'intensité des incendies est un indicateur déterminant du comportement du feu. Il pourrait être aussi un important indicateur de nombreux types de dynamiques écologiques. Il s'est toutefois avéré difficile à mesurer directement. Les estimations indirectes sont souvent assimilées aux effets écologiques des incendies, ce qui empêche d'étudier plus à fond les relations entre l'intensité des incendies et les dynamiques des populations ou communautés. Dans le présent rapport, nous décrivons une méthode innovatrice pour estimer l'intensité des incendies dans la forêt boréale de l'Ontario, en utilisant des images haute définition prises peu après les incendies. Cette méthode repose sur les relations empiriques entre la structure des branches des arbres détruits par le feu (la partie des cimes qui est brûlée) et les degrés d'intensité du feu obtenus grâce à la *méthode canadienne de prévision du comportement des incendies de forêt (PCI)*, et au guide de terrain qui y est associé (le guide est destiné aux chefs des services de lutte contre les incendies). Nous décrivons les résultats obtenus après avoir associé cette méthode à des photos aériennes haute définition (660) que nous avons prises de placettes d'échantillonnage d'un diamètre de 25 m^2, réparties entre 11 incendies qui ont eu lieu dans la forêt boréale de l'Ontario en 2005. Nous avons pu classer l'intensité des incendies dans cinq groupes, qui sont équivalents aux intensités suivantes obtenues par la *méthode PCI* : moins de 10 kW/m^2, de 10 à 500 kW/m^2, de 500 à 2 000 kW/m^2, de 2 000 à 4 000 kW/m^2 et de plus de 4 000 kW/m^2. La méthode proposée pourrait être une bonne solution de rechange aux coûteux instruments nécessaires pour mesurer au sol l'intensité des incendies. Elle pourrait aussi être utile aux aménagistes forestiers et aux chefs des services de lutte contre les incendies de forêt, de même que pour la recherche sur l'interaction entre les incendies et les forêts sur plusieurs échelles.

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Introduction

Many of the complex behaviours exhibited by forest fires, for example, their variable modes of spread and unpredictable fuel consumption patterns, are correlated with the local energy generated by the fire per unit time, termed *fire intensity* (Byram 1959). Although spread, fuel consumption, and intensity can interact with landscape and weather in complex non-linear ways, fire intensity remains central to fire behaviour in many situations and is sometimes used as a summary statistic to compare differences within and among fires (Van Wagner 1977). Fire intensity is also used in ecology as a measure of the force that is the initial cause of all fire-related ecological change. Under certain scenarios and assumptions, individual, population, and community dynamics may be modelled as functions of fire intensity to test hypotheses about the influence of fire on ecological systems. To advance our understanding of fire-forest interactions, which play a significant role in the trajectories of many forest ecosystems, we need to understand the non-linear relationships between fire behaviour and ecological dynamics. As a possible step in this process, and without assuming any specific knowledge of the relationship between fire intensity and ecological effects *per se*, we propose a new method for approximating fire intensity in the boreal forest using post-fire high resolution aerial photographs. This approach may be useful in forest and fire management applications, as well as for research on fire-forest interactions at a variety of spatial, temporal, and ecological scales.

Importance of fire intensity in ecology

While many reports in the literature mention fire intensity and its effects on forests and landscapes, few directly confront the problems inherent in obtaining estimates of fire intensity (Moreno and Oechel 1989). Yet an understanding of the ecological effects of fire intensity is crucial to a range of applied research. For example, more research is needed to understand the relationship between fire intensity and post-fire succession (Whittle et al. 1997) and in determining the resilience of forest ecosystems to fire (Henig-Sever et al. 2001).

Considerable evidence exists that different communities respond differently to fire intensity. The success of aspen (*Populus spp.)* suckers in burned areas where fire intensities were low, versus the high fire intensities required to trigger seed release in the serotinous cones of jack pines (*Pinus banksiana*) provide two examples (de Groot et al., 2004, Bartos and Mueggler 1981, Horton and Hopkins 1966). However, we do not yet understand the ultimate aggregated response of mixed communities as a function of these simple species-wise trends. Using mathematical models, Johnson and Gutsell (1994) have predicted a potential increase in the frequency and severity of forest fires as a result of climate change. In that case, an understanding of fire effects may become increasingly important for conserving natural resources.

Fire intensity affects animal populations as well. For example, high intensity fires can be used to control populations of insects (buffington 1967; Miller 1979 and McMullen et al. 1986). On the other hand, beetle populations thrive in forest stands that are weakened by damage from low intensity fires (Jakubas et al. 1994). Fire intensity can affect the carrying capacity of moose populations in post-burn landscapes (Spencer and Hakala 1964; Wolff and Zasada 1979). Within a given family, different species may respond differently to fire intensity. For example, Ellison (1975) suggests that post-fire blue grouse (*Dendragapus spp.)* population dynamics are relatively independent of fire intensity, whereas ruffed grouse (*Bonasa umbellus*) and spruce grouse (*Falcipennis Canadensis*) do best in low intensity fires where residual trees occur and the organic layer of the soil is relatively intact.

Fire effects on soil depend greatly on its intensity (Andreu et al. 1996). High fire intensities consume the organic or duff layer, which before fire acts like a sponge: releasing rain water gradually into the watershed. If the duff layer is consumed by high-intensity fires, not only is soil more at risk to erosion, but nutrients that would have been cycled through the soil will run unrestricted over the surface (Rice 1993, Andreu et al. 1996, Inbar et al. 1998, Gimeno-Garcia et al. 2000). In extremely intense fires, soil can become hydrophobic (Certini 2005).

Measuring fire intensity

Despite its broad applicability to ecosystem dynamics as described briefly above, fire intensity has proven difficult to measure. Direct estimates are difficult to obtain since we cannot predict where and when a fire will occur with enough precision to install instruments

in advance. As a result, most fire intensity data is from instruments placed in small planned fires (Kennard et al. 2005). However, many studies of fire behaviour and ecology require fire intensity data collected over larger areas (e.g., many hectares) and at higher resolutions (e.g., on the order of metres) than is available from such direct measurements.

As a result, indirect estimates of fire intensity are often used instead. In planned fires, intensity can be estimated indirectly using measures of fuel consumption and rates of spread. In wild fires, indirect estimates of fire intensity usually rely on correlations between the ecological effects of a forest fire, often termed *fire severity* (Whelan 1995), and its intensity. Tree mortality (Alexander 1982, Schmidt and Vlok 2002), the diameter of burned branches (Moreno and Oechel 1989), the pH of ash (Henig-Sever et al. 2001), and soil microarthropod community structure (Henig-Sever et al. 2001) have all been used as indirect severity-based measures of fire intensity. Fire managers can also use their experience to integrate fire weather data with observations of site damage to obtain an estimate of fire severity.

A drawback to severity-based measures of fire intensity is that they assume a monotonic relationship between fire intensity and ecological impacts. For instance, although tree mortality and fire intensity are correlated (McMullen et al.1986), this effect varies from species to species (Whittle et al. 1997). The amount of a living branch that is consumed by a fire also probably depends, among other things, on the physiology of the tree species (Hely et al. 2003). Using tree mortality or burned branch diameter as a surrogate for fire intensity then restricts inferences about the ecological effects of a fire, since this intensity-mortality correlation is itself influenced by patterns in community structure. Similarly, while the physical and biotic structure of the soil are also influenced by fire intensity (Rice 1993, Andreu et al. 1996, Inbar et al. 1998, Gimeno-Garcia et al. 2000, Certini 2005), interplay is likely among the physical, chemical, and community aspects of soil structure in the aggregate response to fire intensity. In sum, a clear understanding of the ecological effect of fires is difficult to obtain if severity-based variables are first used as estimates of fire intensity, since such estimates embed the relationships being studied into the data *a priori*, by assuming a monotonic relationship between ecological effects and fire intensity.

Study objectives

We investigated whether fire intensity could be estimated, albeit roughly, using post-fire data that was not directly related to ecological effects and did not require expert knowledge to integrate weather and fuel information. By definition, such data would have to be independent of the distribution and abundance of living organisms in post-fire sites (i.e., mortality-independent). In addition, the data should be independent of physiological damage to living organisms, since tolerances to physiological damage vary from species to species and influence mortality rates. Yet this post-fire data needs to be empirically correlated with fire behaviour in such a way that a crude estimate of intensity can be inferred.

The Canadian Forest Fire Behaviour Prediction System (FBP), which provides much of the scientific basis for forest fire research as well as informing fire suppression practices, uses crown fraction burned (CFB) to describe fire behaviour on a continuum from creeping surface fires to crown fires (Forestry Canada Fire Danger Group 1992). Each type of fire is in turn related to a broad fire intensity rank (e.g., Taylor et al. 1996).

We propose that the proportion of the fine branch structure of fire-killed trees (hereafter referred to as *snags*) that is destroyed by fire can be used as surrogate for CFB and then related to fire intensity rank based on the FBP. By considering only snags, this procedure divorces itself from patterns in mortality (i.e., a ratio of live to dead trees). Physiological damage also thus becomes irrelevant since the snags are dead. While the same fire intensity may elicit different patterns in CFB in different species or site conditions, we assume that the intensity ranks are sufficiently broad that between-rank variability should not be influenced significantly by such differences.

The objectives of this report are (1) to describe this proposed method of estimating fire intensity rankings from post-fire observations and (2) to briefly document the fire intensity data acquired using this method to illustrate the method's potential for research applications.

Materials and Methods

Fire intensity rankings

In the FBP, fire intensity is categorized using a five-rank system (Table 1). Each rank is associated with a particular range of intensities, and a proportion CFB (see Table 2 for glossary of terms used in this report). Very low-intensity fires (Rank 1, < 10 kW·m^{-1}) usually smolder and only affect trees by damaging the roots, leaving the branch structure intact. As intensity increases to 10 - 500 kW·m^{-1} (Rank 2), the flame length, rate of spread, and fuel consumption also increases. Such fires cause charring of the trunk but leave the fine branches unconsumed since fuel is provided solely from the duff layer of the soil and small ground vegetation. When fire intensity is 500 - 2000 kW·m^{-1} intensity (Rank 3), increased flame length leads to partial destruction of the fine branch structure. For intensities between 2000 - 4000 kW·m^{-1} (Rank 4), small clumps of trees will be engulfed by flame, leaving little or no fine branch structure intact. Fires with an intensity >4000 kW·m^{-1} (Rank 5) travel in the crowns of trees, leaving no intact branches (Figure 1).

Table 1. *Empirical relationship between fire intensity rank and the crown fraction burned – here snag fine branch structure destroyed – based on the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992).*

Fire intensity rank	Fire intensity (kW·m^{-1})	Fire type	Snag fine branch structure destroyed (%)
1	< 10	Smoldering	0
2	10 - 500	Creeping surface	0
3	500 - 2000	Surface	< 10
4	2000 - 4000	Intermittent crown	10 - 90
5	> 4000	Continuous crown	> 90

Table 2. *Glossary of terms as used in this report.*

Term	Description
Crown fraction burned	The proportion of a tree's crown affected by the fire
Fine branch structure	Secondary branches not immediately connected to the trunk
Fine branch destruction	The relative extent to which fine branch structure is absent. This is used as a surrogate for crown fraction burned.
Fire intensity	The local energy generated by the fire per second in kW·m^{-1}
Fire severity	The ecological effects of a fire
Snag	A fire-killed standing tree
Torching	When fire consumes the fine branch structure of a tree or snag

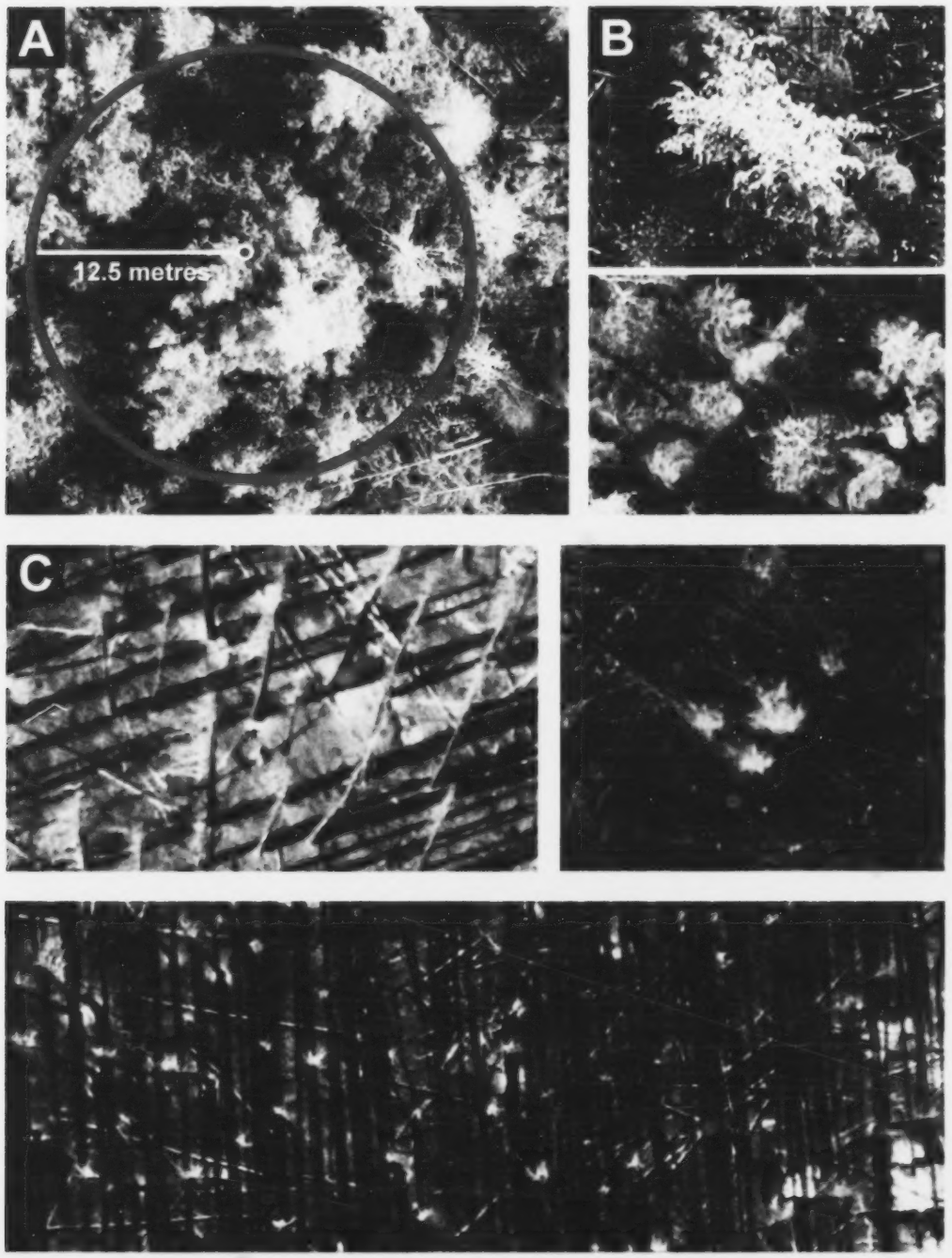


***Figure 1**. Examples of: (A) A high resolution photograph (HRP) image showing the perimeter and centre of a sample plot lacking any visible signs of fire. This plot would be classified as having a fire intensity rank of 1. (B) Trees damaged by convective heat from fires of intensity ranks 2 or 3. (C) Remnants of trees with their fine branch structure destroyed, as would occur during fires of intensity ranks 4 or 5.*

Using the proportion of a snags' fine branch structure destroyed by fire as a surrogate for CFB, we can associate snag condition in each sample plot with a fire intensity rank. In theory, more intense fires have a higher probability of enveloping the entire tree and/or travelling across the crowns of trees since intensity is correlated with flame length and higher intensity fires can combust a wider range of potential fuels (Byram 1959). Examining snags to determine the fraction of the branch structure consumed by the fire thus provides a crude estimate of fire intensity without relying on measurements of physiological damage, mortality, or changes in relative abundance of species. While these latter variables are important to many areas of forest and fire research, they are unreliable estimators of fire intensity because of their complex relationship with fire behaviour.

Ranking method

We used the condition of the fine branches on post-fire snags to estimate fire intensity by way of a dichotomous key which classified the average condition of snags in sample plots (Figure 2). This key contains the decision steps in our proposed method, which are expanded upon below. After assigning all plots composed of 75% contiguous unburned areas to intensity Rank 1 (Figure 3), Rank 2 plots were easily discernable as those with no evidence of fine branch destruction (Figure 4). The 75% cutoff was chosen arbitrarily with the intent of distinguishing plots with the majority of their area visibly affected by fire. Where almost all fine branch structure was destroyed, the plot was assigned to Rank 5 (Figure 5). All remaining plots were classified as Rank 3 or 4 depending on the degree of fine branch destruction (Figures 6 and 7). We assumed that fire intensity was constant within a plot and that every dead tree constituted a replicate instrument with which fire intensity was measured via remaining branch structure.

We found that most snags (post-fire) within a plot had the same branch structure. Snags that retain their fine branch structure tend to look similar to live trees, but with a brown or grey coloration in photographs. The main branches and trunk are usually obscured

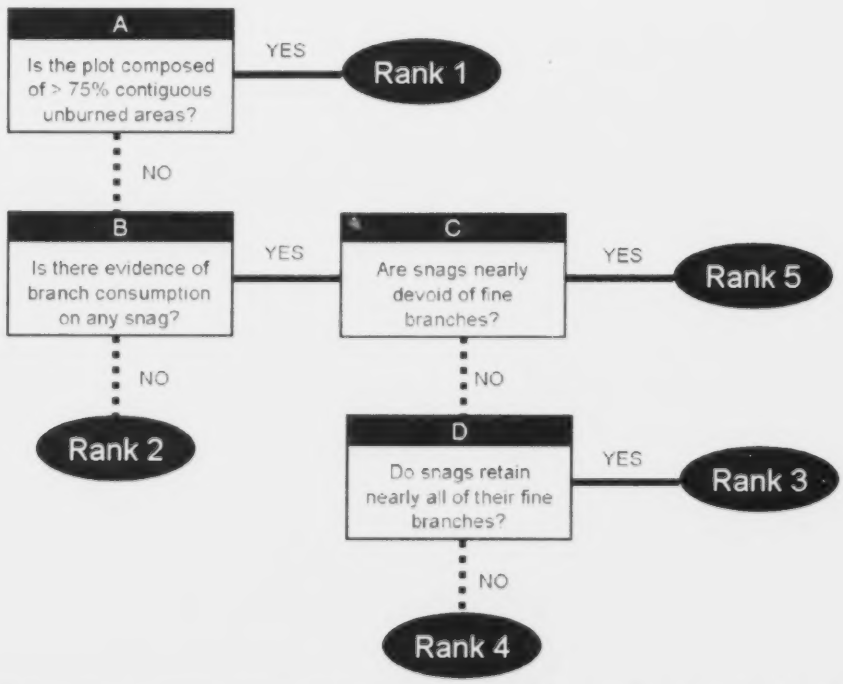
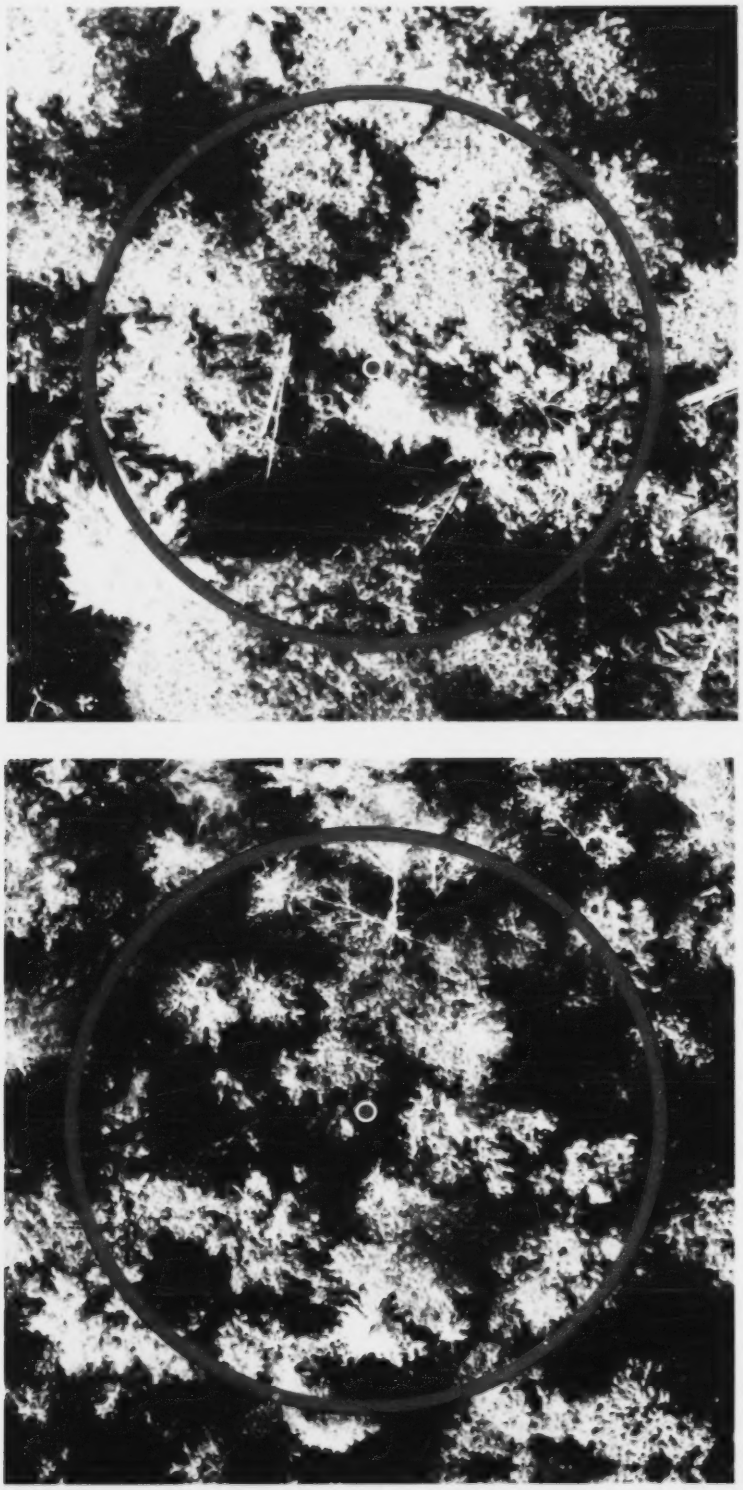
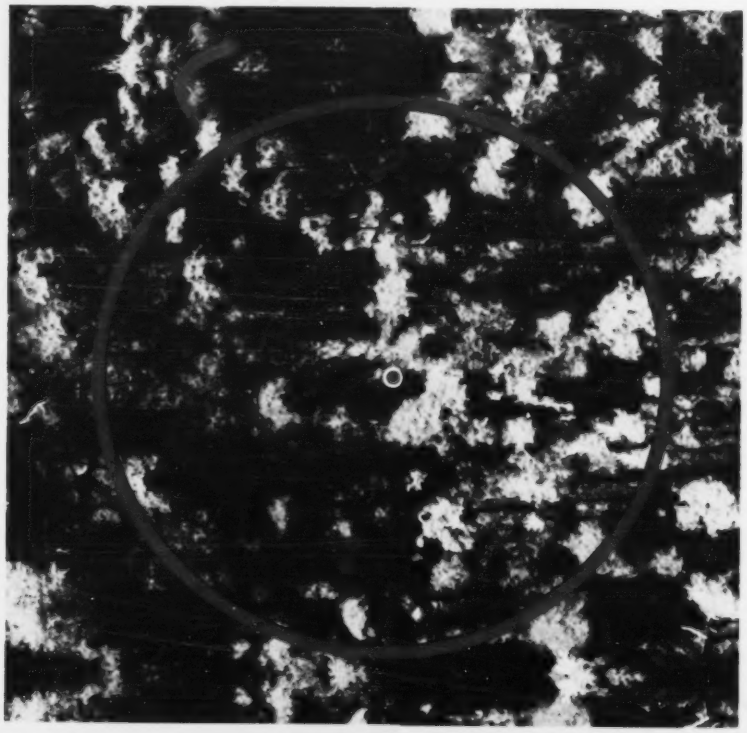


Figure 2. *Dichotomous key developed to classify the fire intensity affecting a 25-m-diameter circular sample plot in the boreal forest, observed using high resolution aerial photography. The key is based on criteria in the Canadian Forest Fire Behaviour Prediction System (FBP) (Forestry Canada Fire Danger Group 1992) and field guide (Taylor et al. 1996)*

***Figure 3**. High resolution photographs illustrating plots that would be classified as fire intensity rank 1 because they have >75% contiguous unburned areas.*





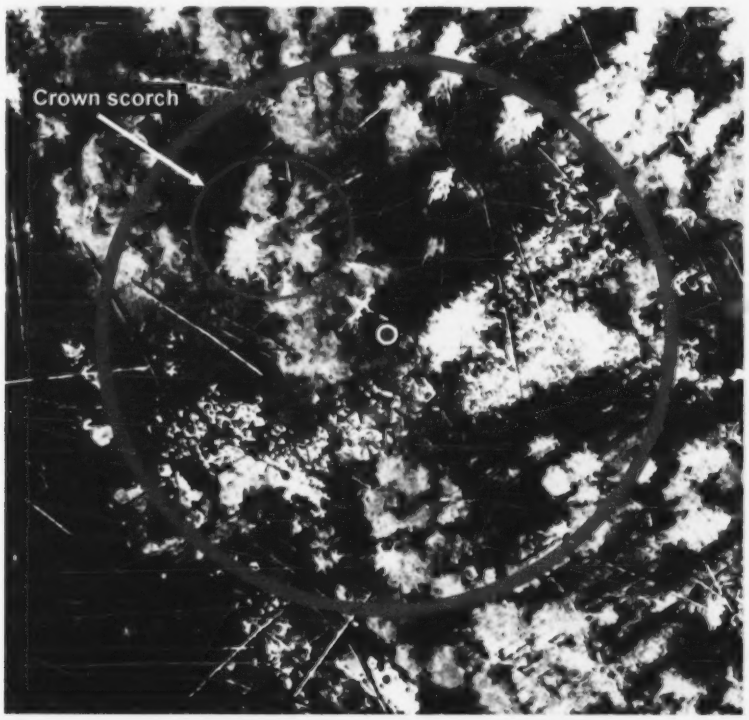
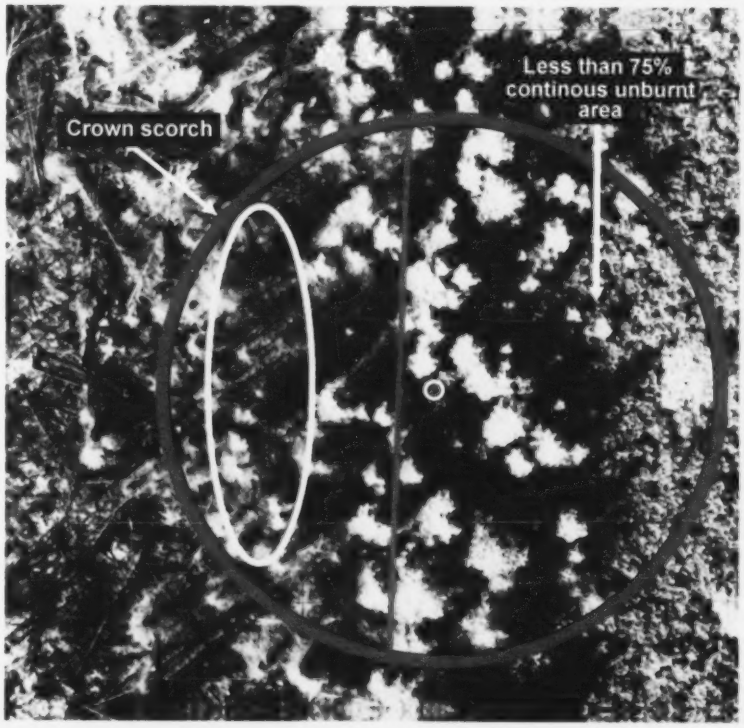
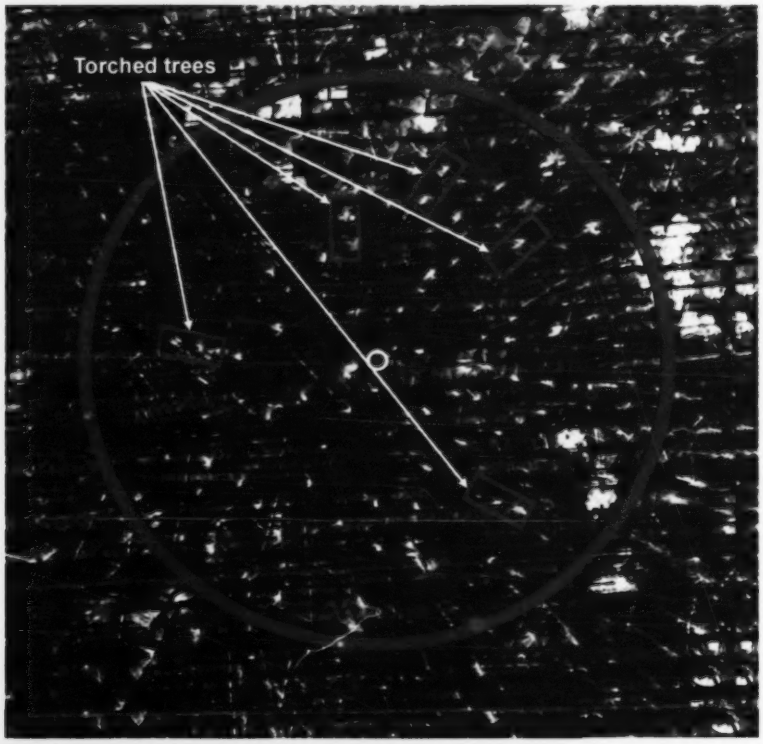


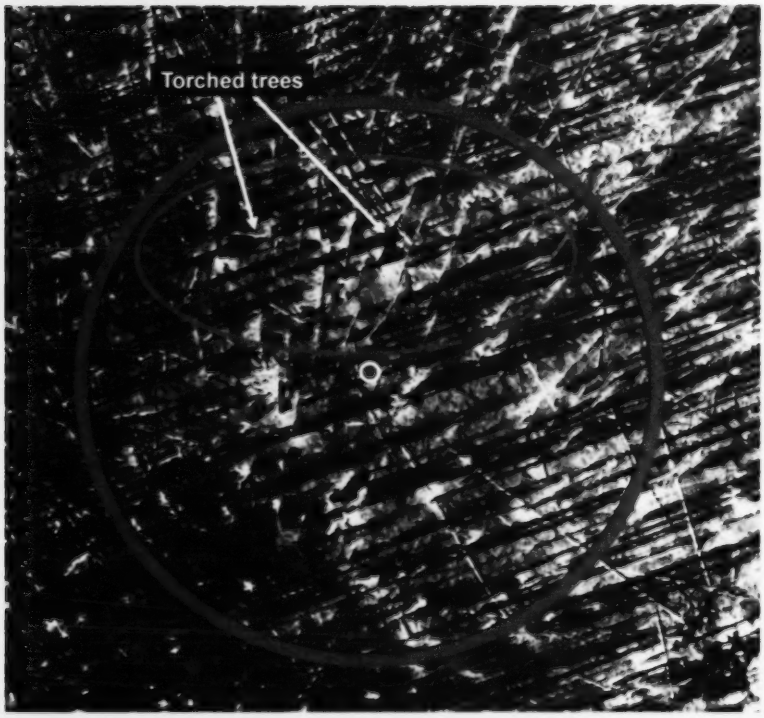
Figure 4. *Examples of plots in high resolution aerial photographs that would be classified as fire intensity rank 2. Although there is evidence of convective heat damage, i.e., crown scorch, no fine branch destruction is visible on snags.*

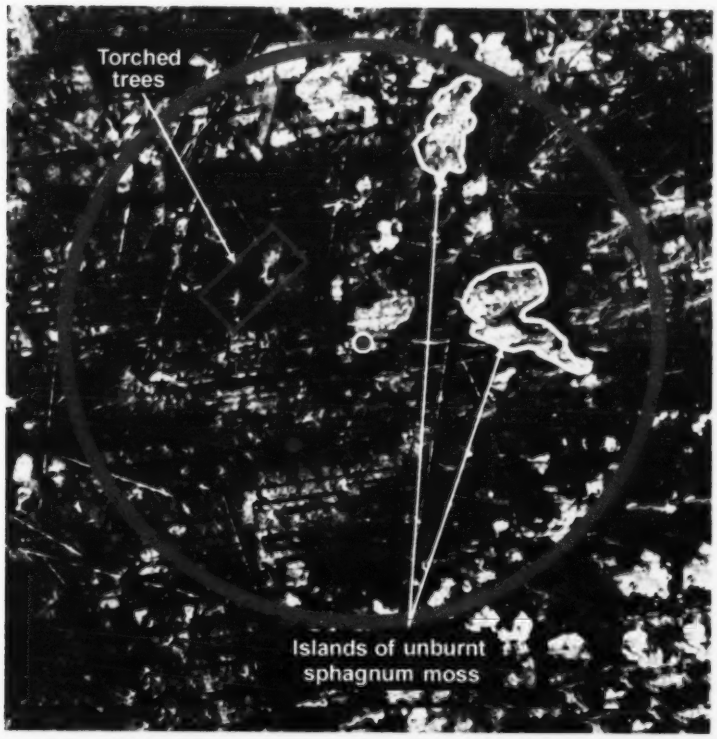

Crown scorch
Less than 75% continous unburnt area

Crown scorch

Figure 5: *Examples of plots in high resolution aerial photographs that would be classified as fire intensity rank 5. Most snags are completely lacking fine branch structure (referred to as torched). Note that new growth and unburned moss can give these photos a green appearance despite the intensity of the fire.*






Torched trees
Islands of unburnt sphagnum moss

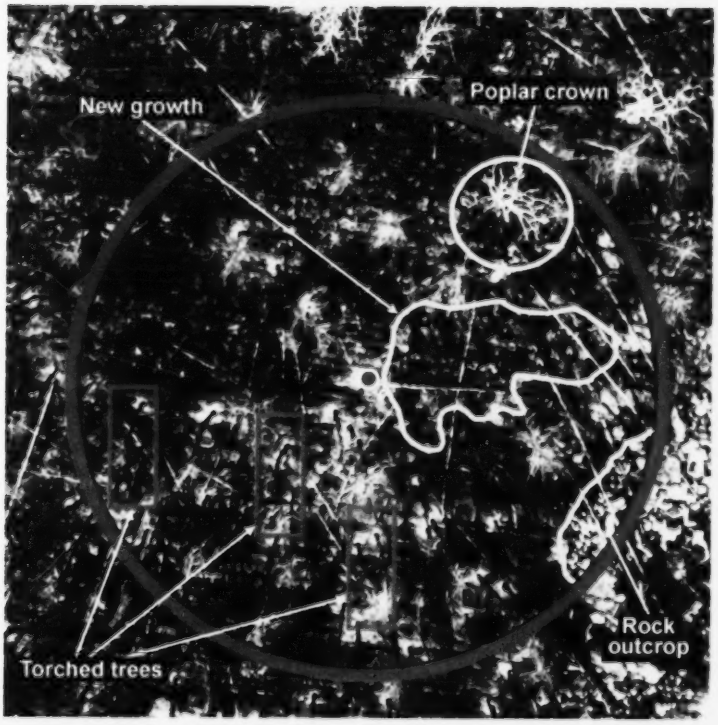
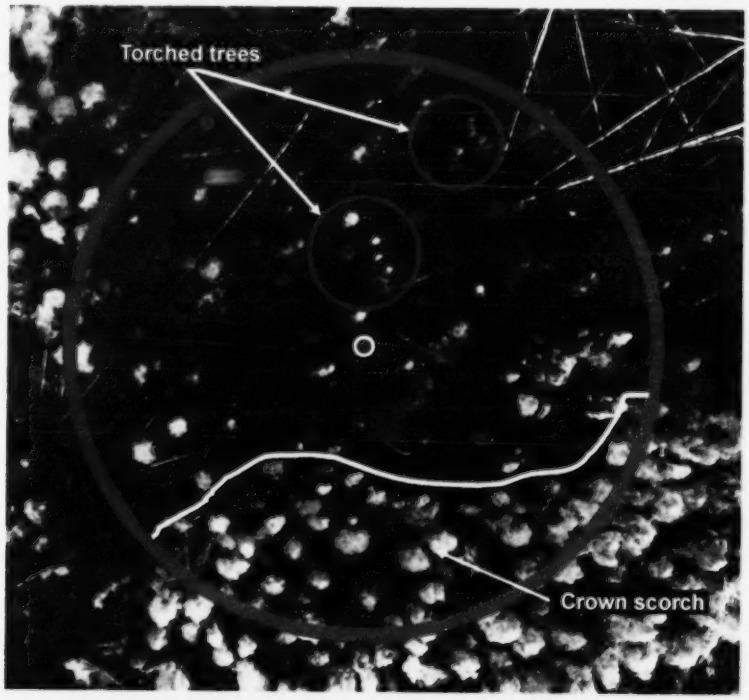

New growth
Poplar crown
Rock outcrop
Torched trees

Figure 6. *Examples of plots in high resolution aerial photographs that would be classified as fire intensity rank 4. Most dead trees are missing 10 to 90% of their fine branch structure (i.e., they are considered torched) but some retain fine branches at the tip of the crown.*



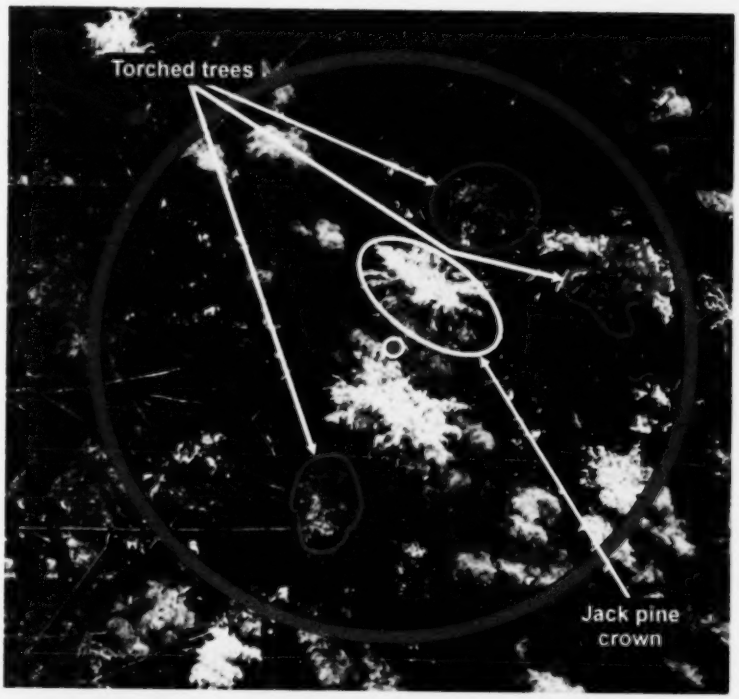
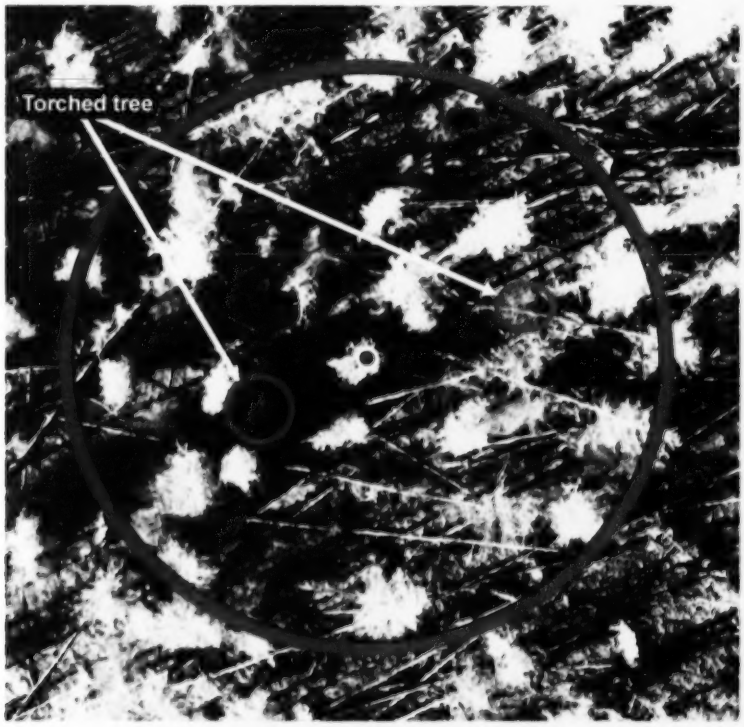
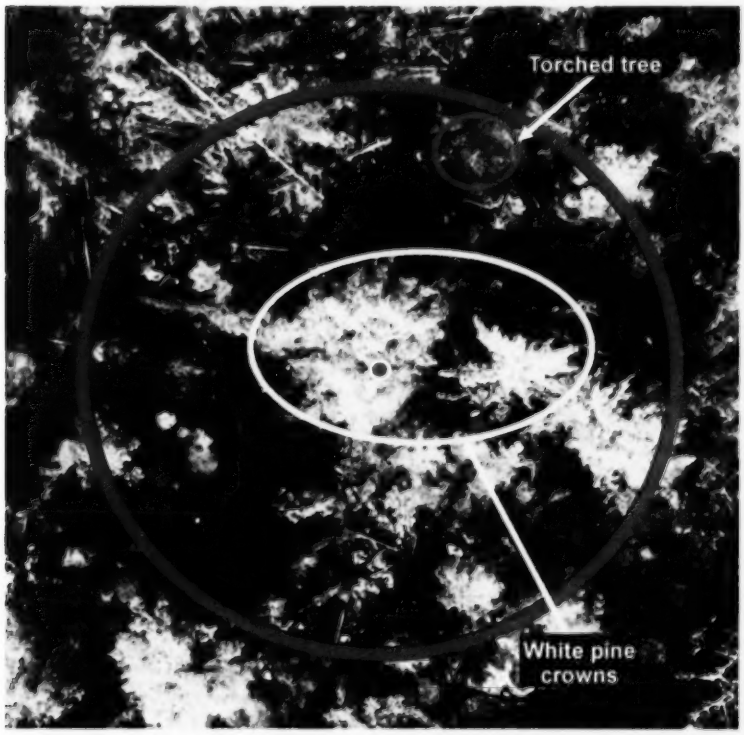

Torched trees
Jack pine
crown

Figure 7. *Examples of plots in high resolution aerial photographs that would be classified as fire intensity rank 3. Although evidence of fine branch destruction (referred to as torching) exists, most snags retain >90% of their fine branch structure.*





Torched tree

Torched tree
Live spruce

by the small branches and residual foliage. In contrast, when snags have their fine branch structure destroyed, the trunk and main branches are clearly visible, and are not covered by smaller branches or foliage. In some cases, residual branch structure and foliage may remain in the upper crown of such snags, giving them a broom-like appearance.

We compared the results of fires intensity rankings obtained using the proposed key to subjective estimates of fire intensity developed for the same sample plots. This subjective estimate was done independently by author, T. Smith, an expert with 10 years experience fighting fires in the boreal forest, extensive experience with ground-surveys of post-fire areas, and knowledge of forest ecology. Smith subjectively integrated data on fire weather, mortality, site conditions, and fuel types to estimate fire intensity for each sample plot, without awareness of the fire intensity assigned using the key.

We used the fire intensity rankings obtained using the proposed method to develop fire intensity surfaces for each of the study fires to illustrate a possible application of this method. Fire intensity surfaces were interpolated from points using the method of Hutchinson (1989) as implemented in ArcGIS 9.1 Spatial Toolbox.

Data

The data we used came from 660, 25-m-diameter circular plots in aerial photographs, captured using high resolution photography (HRP). However, the method we describe does not require HRP data. It can be used with any data on the branch structure of groups of post-fire snags. The plots we measured were dispersed across 11 fires that occurred in the boreal forest of northern Ontario in 2005 (Table 3, Figure 8). The plots were located 300 m apart along east-west transects to systematically sample each fire. Areas of the fires that were suppressed, or subjected to pre-fire harvesting or post-fire salvage, were not included in this 660-plot data set.

The photos were taken using a helicopter with a boom attachment with cameras mounted 6.1 m apart on the boom that captured automated stereo photographs of the plots based on global positioning system (GPS) input (Figure 9). The focal length of the camera was 100 mm and the photos were captured on ASA colour portrait 70 mm film. The

Table 3. *Details of the 11 study fires that burned in 2005, including the MNR fire number, the management region in which fire occurred, the coordinates of the centre of the fire, the corresponding UTM zone, the number of sample points in and the area of the fire, and the Fire Weather Index (FWI), Initial Spread Index (ISI), and Buildup Index (BUI). Fire weather statistics are for the fire start date. Data are from MNR's Daily Fire Operations Support System.*

MNR Fire Number	Region	Easting (m)	Northing (m)	UTM Zone	Sample points	Fire area (ha)	FWI1	ISI1	BUI1
CHA-018	3E	35750	535150	17	(#)	54	34.19	10.79	107.13
COC-010	3E	49050	547750	17	7	347	32.56	19.67	42.02
FOR-014	4W	59950	534950	15	31	430	13.80	5.06	52.85
FOR-024	4W	62110	533700	15	32	213	8.77	3.81	35.91
NIP-020	3W	43050	559950	16	18	13600	26.84	12.57	52.84
THU-030	3W	37650	560450	16	309	429	11.45	4.07	51.55
THU-031	3W	37350	557250	16	32	1429	11.45	4.07	51.55
THU-067	3W	30650	556150	16	84	2325	12.41	4.30	54.93
TIM-005	3E	44050	529050	17	83	440	16.16	7.43	41.03
TIM-007	3E	40860	533790	17	27	450	13.74	6.64	35.58
TIM-019	3E	51650	534650	17	20	3200	26.50	7.78	99.48

1 FWI, ISI, and BUI are based on the Canadian Forest Fire Behaviour Prediction System (Forestry Canada Fire Danger Group 1992).

Figure 8. *Map of the study area showing the 11 study fires, labelled by MNR fire number designations, in three ecoregions in Ontario's boreal forest. (See Table 3 for details about the fires.)*

Figure 9. *The helicopter and boom attachment used to acquire the high resolution photographs for this study.*

photos were taken at an altitude of approximately 100 m (for details see Routledge 2007). As stated, the method presented here can, in theory, be applied wherever data on the fine branch structure of snags is available. Thus the equipment required to gather the necessary measurements may vary from study to study.

Aerial photography has been used before to measure the effects of forest fires (e.g., Brais et al. 2000, Asbjornsen 2005). One advantage to HRPs is the high resolution per pixel, allowing the condition and branch structure of individual trees to be visually assessed with the naked eye. Ideally, the photos should be taken immediately after the fire. As lag time between the photo and the fire increases, the branch structure of snags may deteriorate, and new growth could obscure the information needed to use the key. In our case, this was avoided because the photographs were taken within one to three months after the fires.

Results

Estimates of fire intensity rank from the proposed method were similar to the expert-assessed intensity ranks (Table 4). In 52% of cases, rankings were identical. Where there was disagreement, differences of a single rank were most common, and the magnitude of the difference between the expert rank and proposed method rank for a plot exceeded one in less than 5% of cases.

Estimated fire intensity showed interesting patterns of within- and among-fire variability. Within fires, intensity appeared to be spatially autocorrelated, with similar fire intensities more likely to occur close together. The distribution of fire intensities varied among fires with some having higher intensity overall than others (Figures 10-12). These distributions had different modes in different fires as shown in Figure 13.

Discussion

The absence of a severity-independent method of estimating fire intensity hinders the ability to test hypotheses about the ecological effects of forest fires. Hypotheses relating fire intensity to ecological dynamics cannot be tested if the same dynamics are first used to estimate intensity: that would be circular reasoning and violate the principles of the scientific method. The method we present here relies on an empirical relationship between post-fire snag CFB, measured as the percentage fine branch structure that is destroyed, and the intensity rank of the fire. Because this method relies on the physical structure of post-fire snags, a sample group that has a constant mortality rate of 1, and for whom physiological damage is irrelevant, it is reasonable to assume that it is relatively species- and site-independent, at least for the purposes of characterizing broad patterns in intensity as in Table 1.

However, the assumption of a CFB–fire intensity relationship may carry different risks in different situations. In particular, a low intensity fire may move sufficiently slowly over an area to increase

Table 4. *Comparison of results of fire intensity rankings obtained from expert-based vs. proposed method for 660 sample plots, as well as the differences in rankings (grey cells indicate rankings between the two methods matched).*

Fire intensity ranking from proposed method	Expert rank					Difference from expert rank					
	1	2	3	4	5	-3	-2	-1	0	1	2
1	26	7	2	0	0	1	4	13	26	0	0
2	13	64	33	2	0	0	11	46	64	7	0
3	4	46	93	23	4	0	2	60	93	33	2
4	1	11	60	95	39	0	0	25	95	23	2
5	0	0	2	25	70	0	0	0	70	39	4

Figure 10: *Spatial distributions of fire intensity rankings for fires CHA-018, COC-010, TIM-007, and FOR-024 (A-D, respectively). See Table 3 for fire details and sampling information.*

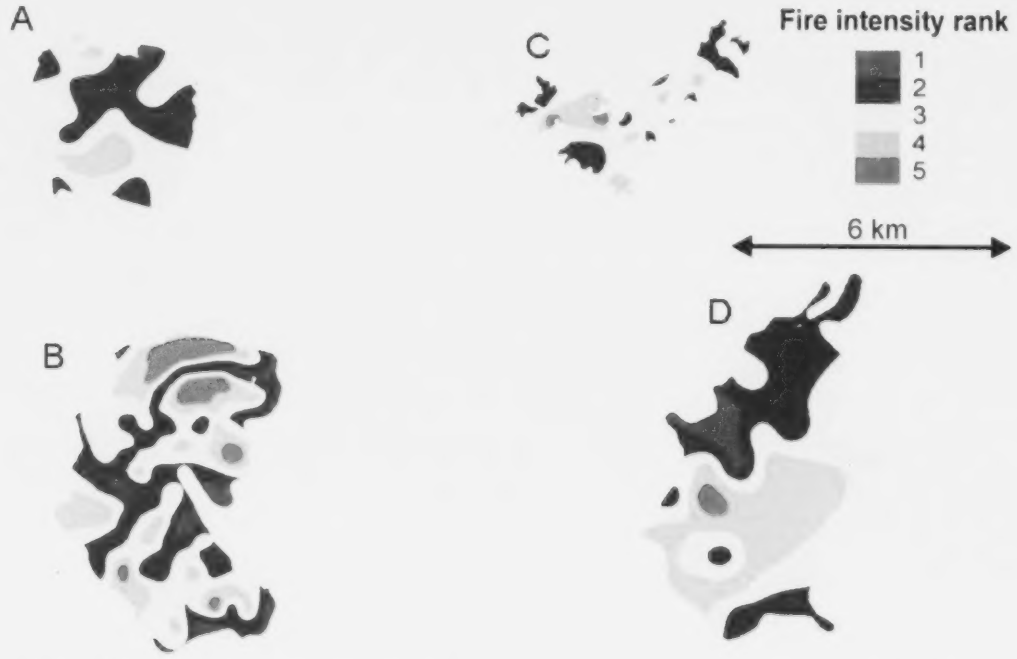


Figure 11. *Spatial distributions of fire intensity rankings for fires FOR-014, THU-031, THU030, TIM-005 (A-D, respectively). See Table 3 for fire details and sampling information.*

Figure 12: *Spatial distributions of fire intensity rankings for fires NIP-020, THU-067, and TIM-019 (A-C, respectively). See Table 3 for fire details and sampling information.*

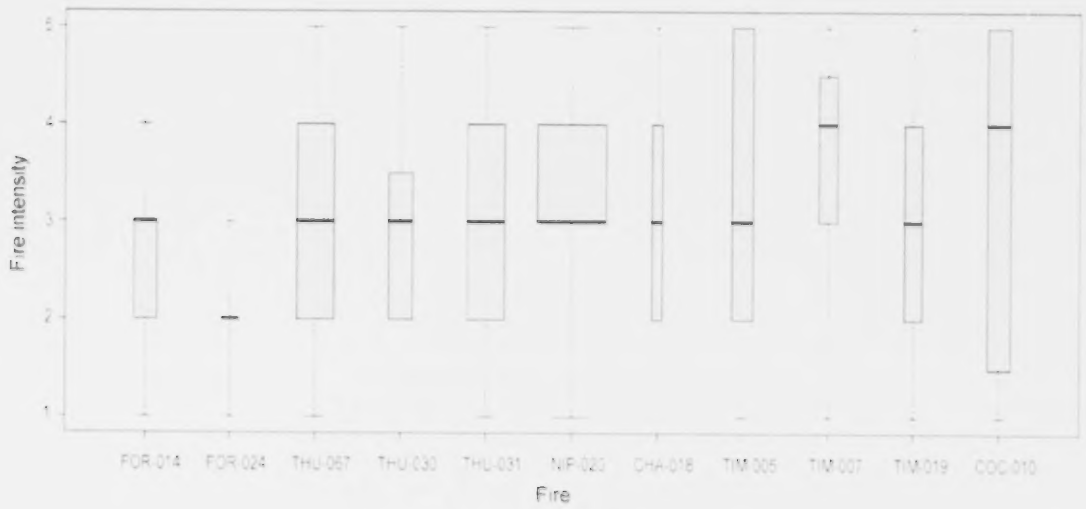


Figure 13. *Boxplots of fire intensity rankings for the 11 study fires. The vertical position and height of the gray boxes show the interquartile range of the data for each fire, while the width is proportional to the relative sample size (given in Table 3). The black line indicates the median, and whiskers enclose the entire range. Fires are arranged geographically from west to east (left to right).*

the probability of extensive crown damage to trees, thus increasing apparent CFB without a corresponding increase in intensity. Also, this method was developed for predominantly boreal conifer stands and may not work as well for mixed or deciduous forests, where intensity may result in different patterns of CFB. Furthermore, where fire intensities greatly exceed 4000 $kW \cdot m^{-1}$, resulting in all plots being designated as having a fire intensity rank of 5, the method will not be sensitive to further variation in fire intensity. However, many areas of the fires we sampled had fire intensity ranks lower than 4 suggesting that, in the fires we studied, intensities greater than 4000 $kW \cdot m^{-1}$ were the exception. So, even if such high intensities occur, they may occupy only part of the fire, indicating that the ranking method still applies to most areas of the fire.

In wild fires, indirect estimates of fire intensity usually have been gleaned from data on tree mortality (Alexander 1982), the diameter of burned branches (Moreno and Oechel 1989), the pH of ash (Henig-Sever et al. 2001), and soil microarthropod community structure (Henig-Sever et al. 2001). In contrast to these methods, which are all based on the assessment of direct ecological effects of the fire, the method proposed here seeks to use supposedly abiotic elements of the ecosystem—snags, in our case—only as replicate instruments, from whose physical structure fire intensity can be inferred.

Of the extant methods for estimating fire intensity that we surveyed, ours most closely resembles the burned branch-diameter technique of Moreno and Oechel (1989). However, an important difference between the methods is that while Moreno and Oechel's method relies on the physiological damage to live and dead trees, which is strongly linked to mortality and varies from species to species, the method we present focuses only on snags and, for those snags, on a characteristic that is most strongly linked to fire behaviour. Specifically, while the trees became snags because of physiological damage caused by fire, by looking at only snags and not live trees we are using a sample of trees that we can assume had equivalent physiological damage. Variation in the CFB of these trees is thus more closely linked to differences in fire behaviour than differences in physiological damage.

The strong agreement between the estimates of fire intensity using our method and the single sample of expert-assessed intensity ranks suggests that excluding ecological information from estimates of fire intensity may introduce extra variability into fire intensity data, thus changing the precision of the estimate but not appreciably changing the accuracy. However, we acknowledge that a rigorous test of this hypothesis would require comparison of our results with those of many more experts. Nonetheless, the method we present here is inductively supported by the FBP and does not rely on expert validation.

The apparent accuracy of the method may be provided in part by its objectivity. In the case of fire intensity ranks 1, 2, and 5, the assessor must answer only simple binary questions. For example, to establish whether or not a plot has a fire intensity rank of 1, they have only to judge whether or not 75% (or another arbitrary high percentage) of the plot is unburned. If the plot is not considered to have a fire intensity rank of 1, but evidence of fine branch destruction is lacking, then it is assigned an intensity rank of 2. On the other hand, if all snags are completely torched then the plot is assigned a fire intensity rank of 5. Finally, if a plot initially appears to be a rank 5 fire intensity, but contains a few untorched snags then it is assigned to rank 4. Otherwise, it is considered to have a fire intensity rank of 3 (see Figure 2). So the application of the key only becomes "fuzzy" with respect to distinguishing between ranks 3 and 4. We think that capturing the salient features of most fires' intensity patterns, as illustrated in the fire intensity maps generated for the study fires (Figures 10-12), may not always depend on such a distinction.

The proposed method has drawbacks as well as implementation challenges. One drawback is the coarseness of its scale: since fire intensity is a continuous variable, lumping it into five classes may obscure much of its variation. Another drawback is its indirectness: CFB is at best a rough estimator of fire intensity category and, as discussed above, may necessitate risky assumptions in some situations. The method becomes more challenging to implement as photo resolution decreases and as within-sample plot heterogeneity increases. Thus, high-resolution data on relatively small, homogeneous areas are most suited to the use of this method.

Conclusions

Fire intensity is important to many areas of ecological research, but it remains difficult to measure. In particular, while experts can readily integrate many sources of information to assess fire intensity subjectively, estimating fire intensity from post-fire data in a repeatable objective fashion has proven difficult. The method we present here is aimed at easing the scientific estimation of fire intensity and relies on a direct inductive relationship with fire behaviour, rather than with tree mortality or physiology. We argue that it is important to avoid relying upon ecological variables as estimates of fire intensity, since these confound the severity of the impact of the fire with its behaviour. We also show, by comparison with subjective expert estimates of fire intensity on the same data, that excluding contextual ecological information in estimates of fire intensity, thereby divorcing it from severity, does not significantly decrease the accuracy of the estimates. Finally, because this method can be rapidly and inexpensively applied at fine resolutions over large areas, classifying the fire intensity over an entire burned area for example, it may be useful in improving understanding of fire behaviour. That said, this method only represents a possible first step and has some severe limitations. First of all, the fire intensity ranks are very broad and may not capture the full range of fire behaviour dynamics. Also, assuming CFB is a surrogate for fire intensity may obscure some ecologically important variability in the response of forest ecosystems to fire. But, as long as safety and economic constraints, combined with a relatively feeble ability to predict forest fire spread patterns, still limit the collection of the necessary direct data, indirect estimates of fire intensity from post-fire measurements, such as the method proposed here, remain important for research in forest and fire ecology.

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